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Transfer factors for Sr as influenced by species Ca uptake and soil Ca availability

D.S. Veresoglou[1], N. Barbayiannis[1], G.C. Zalidis[2], S. Kalpakis[1] and E. Batianis[1]
[1]*Aristotle University of Thessaloniki, Faculty of Agriculture, Laboratories of Ecology and Soil Science, 54006 Thessaloniki, Greece and* [2]*Greek Biotope/Wetland Centre, 14th Km Thessaloniki-Mihaniona, 57001 Thermi, Greece*

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Abstract

Strontium (Sr) and calcium (Ca) concentrations were studied in different plant species grown in five soil treatments. For either shoots or roots, a positive linear relationship was found between Sr and Ca concentrations in different plant species grown in the same soil treatment. Strontium and calcium concentrations of different species were related to the soil selectivity coefficient for Sr and Ca, defined as the ratio of CH_3COONH_4-extractable Sr and Ca to the ratio of Sr and Ca in the soil solution. For the species used in all soils, transfer factors (TF) for Sr, defined as the ratios of the Sr amount per g of dry plant material and the Sr amount per g of dry soil, were negatively correlated with extractable Ca of the soil. Transfer factors for Sr varied greatly among species or between roots and shoots. This variation of transfer factor was reduced when transfer factor values were divided by the shoot or root Ca concentration of each species. The proposed index TF for Sr per Ca concentration could be used to compare various soils according to their ability to supply plants with Sr when different plant species are grown in these soils.

Introduction

Plant uptake of Sr from Sr contaminated soils was found to be related to soil physicochemical characteristics like pH, organic matter content and competing cations (Khasawneh et al., 1968; Menzel and Heald, 1959; Papanicolaou et al., 1991). Furthermore, Bowen and Dymond (1956), Fleming (1963) and Vose and Koontz (1959) found that plant species normally absorbing large amounts of Ca have the ability to take up more Sr from a culture solution with a given Sr concentration. This is attributed to the chemical similarity between Sr and Ca and the lack of discrimination between the two cations by plants (Bowen and Dymond, 1956; Menzel and Heald, 1959; Rediske and Selders, 1953). This would lead to a positive relationship between Sr and Ca concentrations of different plant species grown in the same medium.

In radioecology, the soil to plant transfer factor (TF), defined as the ratio of the amount of radionuclide per g of dry plant material and the amount per g dry soil (Lembrechts et al., 1990), has been proposed for comparisons of radionuclide transfer from soil to plants. Transfer factors can be used for comparing plant species in taking up radionuclides when grown in the same soil or comparing different soils in supplying plants of a particular species with a radionuclide.

Concentrations of stable Sr, ^{85}Sr and ^{90}Sr were found to vary greatly among plant species or among plant parts of one particular species (Andersen, 1963; Bowen and Dymond, 1956; Fleming, 1963; Papanicolaou et al., 1991; Veresoglou and Fitter, 1984; Vose and Koontz, 1959). For such cases TF for Sr cannot be used for comparing different soils when different plant species are grown in these soils. If Sr concentrations in plants are related to those of Ca, variation in TF values for Sr in different plant species grown in the same soil could be reduced when the species' TF values for Sr are divided by the respective Ca concentrations in plants.

The aims of this study were (a) to examine if any relationship exists between shoot or root Sr and Ca concentrations of plant species grown in the same growth medium, (b) to compare TF for Sr of the species tested and (c) to find a way to reduce the variation in TF for Sr among species so that this index can be used for soil comparisons in which different plant species were grown.

In this study various plant species, belonging to different families and having different Ca requirements, were grown in soils differing in their physicochemical characteristics.

Materials and methods

Two pot experiments were conducted. In the first experiment three soil treatments were used, i.e. the inorganic soil (Soil 1, Table 1) with two Ca additions and the organic soil (Soil 2, Table 1). Pots were filled with respectively 1400 or 320 g of the air dried and sieved (2-mm) inorganic or organic soil. In the inorganic soil only, calcium was added at the rates of 0 and 1.18 g Ca per pot (0 and 0.84 g Ca kg^{-1}), in the form of $CaCO_3$. Addition of $CaCO_3$ caused an increase in pH from 7.2±0.1 to 7.6±0.1 (mean±SE). Each pot received 67 mg of Sr, which corresponds to 47.9 mg Sr kg^{-1} for the inorganic and to 209.4 mg Sr kg^{-1} for the organic soil, in the chloride form. Both Sr and Ca compounds were mixed well with the soil separately for each pot. This procedure, i.e. soil to be weighed and Sr to be applied separately for each pot, was used to minimise variability in the soil Sr content per pot. Twenty days after Sr application the seeds of different species were sown in monocultures and 15 days later 70 mg N and 15 mg P per pot, i.e. 50 mg N and 10.7 mg P kg^{-1} for the inorganic and 219 mg N and 46.9 mg P kg^{-1} for the organic soil, in the forms of NH_4NO_3 and superphosphate, respectively, were added in the solution form. The nine plant species used were the grasses *Anthoxanthum odoratum, Lolium perenne* and *Dactylis glomerata*, the legumes *Medicago sativa, Lotus corniculatus* and *Trifolium repens*, and the forbs *Plantago major, Rumex crispus* and *Plantago lanceolata* (nomenclature follows Tutin et al., 1964–80). They were selected with the criterion to differ in their Ca requirements (Loneragan and Snowball, 1969). Pots were arranged in a completely randomised design with three replicates.

The experiment was conducted in glasshouse during winter. Temperature was kept at 25±3 and 20±2°C during the day and night, respectively. Supplementary light was provided for 12 h during the day. Relative air humidity was about 90%. The soils were kept at field capacity by subirrigation. Twenty days after sowing the seedlings were thinned to 20 per pot for grasses and 10 per pot for the other species.

Shoots were harvested twice, 2 and 3 months after sowing. Although *Anthoxanthum odoratum* was harvested in the first cut, it was not taken into account in the chemical analysis because of poor growth.

At the end of the experiment, the soil was dried, crushed gently, and sieved through a 2-mm sieve and the three replicates of each soil × species treatment were mixed. Two replicates from each of the 27 soil × species treatments were used for soil analyses. Both Ca and Sr were extracted with 1 *M* CH_3COONH_4 at pH 7 and the soil solution was obtained from rewetted soil samples using the centrifuge method of Adams et al. (1980).

In the second experiment, pots were filled with 1350 g of an air dried and sieved (2-mm) inorganic soil (Soil 3, Table 1). Since in the area from which the soil was taken phosphorus was limiting for plant growth (Elisseou, 1994), P in two levels, 0 and 21.8 mg P per pot, i.e. 0 and 16.1 mg P kg^{-1}, was added in the form of $NH_4H_2PO_4$. For pots without P addition, nitrogen was compensated for by NH_4NO_3 addition. All pots received Sr at the rate of 25 mg Sr per pot, i.e. 18.5 mg Sr kg^{-1}, as $SrCl_2$. All elements were added in a solution form and were mixed well with the soil separately for each pot 30 days before sowing. One species was sown in each pot. The six plant species used in this experiment were the perennial grasses *Anthoxanthum odoratum* and *Poa trivialis*, the perennial legume *Lotus corniculatus* and the annual legumes *Trifolium campestre*, *Trifolium subterraneum* and *Trifolium tenuifolium*. These species are common in the area from which the soil was taken. All pots were arranged in a completely randomised design with four replicates.

The growth conditions were the same as those described in Experiment 1. The seedlings were thinned to 20 for grasses and 10 for legumes 25 days after sowing.

Shoots were harvested 3 months after sowing. Roots were separated from the soil and washed. For both experiments plant material was dried at 80°C for 48 h, weighed and ground. A portion of the ground material was dry-ashed in an oven at 450°C for 4 h, and the ash was dissolved in 2 *M* HCl. Concentrations of Sr and Ca in plant material were measured by atomic absorption spectroscopy.

Table 1. Characteristics of soils used in Experiments 1 and 2

Soil	pH[b]	Organic matter[c] (g kg^{-1})	Extractable Ca (mmol kg^{-1})	C.E.C (mmol(+) kg^{-1})
1.Inorganic[1a]	7.2	78 (28)	62.5	154
2.Organic[1]	5.4	862 (330)	250.0	550
3.Inorganic[2]	4.7	35 (11)	22.5	63

[a] Figures refer to the experiment in which the soil was used.
[b] pH was measured in 0.01 *M* $CaCl_2$.
[c] Values of organic matter refer to loss of weight after 2 h at 450°C and, in parentheses, to loss after wet oxidation.

Calculations and statistical analyses

Dry weight and concentrations of Ca and Sr were measured for shoots in Experiment 1 and for both shoots and roots in Experiment 2. We used the ratios of dry weight and Sr concentration in shoots and roots from Experiment 2 to estimate total Sr of roots in Experiment 1. The root:shoot ratios for the species used were similar to those found by Elisseou (1994) for the same species. We calculated the index TF for Sr by dividing Sr concentration of plant material by the concentration of the remaining Sr in the soil. The proposed index, TF for Sr per Ca concentration, was calculated by dividing TF for Sr by the species' Ca concentration.

All these data were subjected to analysis of variance, which in Experiment 1 was made only for shoots and separately for each harvest. Linear regressions were performed between Sr and Ca concentrations in shoots or roots.

Results and discussion

In Experiment 1, shoot weight was affected by both main factors and their interaction (data not shown). Effects were more pronounced in the first harvest in which the grass species and *T. repens* yielded less in the organic soil and the legume species yielded more when Ca was added in the inorganic soil. In the second harvest *Lotus* yielded more only when Ca was added and *T. repens* yielded less only when it was grown in the organic soil.

Table 2 shows that both main factors, species and type of soil, and their interaction affected both Ca and Sr concentrations in shoots of the nine plant species used in Experiment 1.

Although Ca addition increased the mean of shoot Ca concentration in both harvests for most species, a significant increase was observed only for *Medicago* in both harvests and *Rumex* in the first harvest.

When grown in the organic soil, all species had higher shoot Ca concentrations in the second harvest. Compared to the other two soil treatments, all species grown in the organic soil, except *Rumex*, had the lowest shoot Ca concentrations in the first harvest, but statistically similar or greater in the second harvest, with the exception of *Medicago*.

For both harvests, most of the species had the lowest Sr concentration when they were grown in the organic soil. Exceptions to this were the grass species in the first harvest, *P. major* in the second harvest and *Rumex* in both harvests.

The addition of Ca decreased the Sr concentration of *T. repens* in the first harvest and tended to increase the Sr concentrations of the legume and forb species in the second harvest; however, significant increases were found only for *Medicago* and all forbs.

Plant species showed substantial differences in both Ca and Sr concentrations. For any soil treatment in either harvest, every grass species had lower shoot Ca and Sr concentration than any legume or forb species. Similar results for Ca were reported by Loneragan and Snowball (1969). Both Sr and Ca concentrations in shoots tended to have the same ranking among plant species for both harvests and the three soils used. Linear regression lines were fitted to the Sr versus Ca relationship (Table 3).

Table 4 gives the ratios of extractable Ca and Sr for the three soils at the end of the experiment. The organic soil had the highest values of extractable Ca and Sr; in the inorganic soil extractable Ca and Sr were increased with the addition of Ca (data not shown). In comparison to extractable Ca and Sr, soil solution concentrations

Table 2. Ca and Sr concentrations in shoots, transfer factor for Sr (Sr TF) and transfer factor for Sr per Ca concentrations (Sr TF/Ca conc.) for the two harvests of the nine plant species grown in the three soil treatments of Experiment 1

Soil treatment	Species	Harvest 1				Harvest 2			
		Concentrations				Concentrations			
		Ca (mg g^{-1})	Sr (μg g^{-1})	Sr TF	Sr TF/Ca conc. ($\times 10^6$)	Ca (mg g^{-1})	Sr (μg g^{-1})	Sr TF	Sr TF/Ca conc. ($\times 10^6$)
Soil 1	*Anthoxanthum*[a]	-	-	-	-	8.6	136	2.86	332
(inorganic)	*Lolium*	8.2	75	1.60	196	7.3	137	2.96	408
	Dactylis	8.6	83	1.75	203	8.1	148	3.14	393
	Medicago	18.5	342	7.29	394	15.0	333	7.24	481
	Lotus	19.7	303	6.52	329	13.1	246	5.42	411
	T.repens	20.5	355	7.78	379	15.7	338	7.81	499
	P.major	33.7	488	10.73	318	31.5	394	9.12	289
	Rumex	16.5	194	4.14	251	14.4	164	3.51	246
	P.lanceolata	22.8	342	7.33	322	18.3	293	6.46	288
Soil 1	*Anthoxanthum*[a]	-	-	-	-	9.5	127	2.67	280
+Ca	*Lolium*	9.3	73	1.57	169	7.3	121	2.62	356
	Dactylis	10.3	104	2.21	216	7.6	163	3.47	461
	Medicago	21.0	339	7.27	346	21.0	466	10.20	488
	Lotus	21.4	327	7.18	335	16.8	276	6.30	374
	T.repens	20.4	289	6.34	312	16.1	340	7.88	491
	P.major	31.8	447	9.89	312	34.1	450	10.30	303
	Rumex	19.2	211	4.50	235	14.7	218	4.69	326
	P.lanceolata	21.9	358	7.64	348	21.0	378	8.30	396
Soil 2	*Anthoxanthum*[a]	-	-	-	-	8.5	62	0.30	35
(organic)	*Lolium*	3.9	68	0.33	84	7.1	68	0.33	46
	Dactylis	4.3	76	0.37	84	6.7	80	0.38	58
	Medicago	9.0	128	0.62	69	12.6	164	0.80	63
	Lotus	11.3	135	0.66	58	18.3	222	1.11	60
	T.repens	14.7	233	1.12	77	18.4	270	1.34	73
	P.major	22.4	307	1.51	68	38.3	435	2.25	59
	Rumex	22.8	195	0.94	74	23.4	278	1.36	58
	P.lanceolata	14.4	298	1.46	100	21.8	323	1.61	74
	LSD (0.05)								
	Soils	0.8	17	0.31	11	0.9	16	0.31	20
	Species	1.2	28	0.50	18	1.6	27	0.54	35
	Soils × Species	2.0	48	0.87	31	2.8	48	0.93	60
CV (%)		7.5	12.2	12.8	8.5	10.7	11.9	12.9	13.0

[a] *Anthoxanthum odoratum* was omitted from the analysis in the first harvest because of the very low yield.
[b] Both main effects and the interaction were significant at $p \leq 0.001$ for all variables shown.

of Ca and Sr were variable, possibly due to rewetting of the soil samples before obtaining the soil solution. However, the ratio of their concentrations had very low variation (Table 4) and it was quite close to the ratio of extractable Ca and Sr.

Khasawneh et al. (1968) proposed for soils the selectivity coefficient, K_c, defined as the ratio of

Table 3. Linear regression equations relating shoot Sr (in $\mu g\ g^{-1}$) and Ca (in $mg\ g^{-1}$) concentrations for the nine species grown in the three soils of Experiment 1

Harvest	Soil treatment	Equation	N	r^2
1	1	Sr = - 42.54 + 17.0 Ca	24	0.91***
1	1+Ca	Sr = - 68.79 + 17.4 Ca	24	0.91***
1	2	Sr = 11.22 + 14.6 Ca	24	0.84***
2	1	Sr = 74.74 + 11.5 Ca	27	0.69***
2	1+Ca	Sr = 54.95 + 13.8 Ca	27	0.76***
2	2	Sr = - 0.89 + 12.3 Ca	27	0.92***

*** $p \leq 0.001$.

Table 4. Means ± standard errors of the Sr/Ca in the extractable and in the soil solution form and of the selectivity coefficient, defined as the ratio of extractable Sr and Ca to the ratio of Sr and Ca in the soil solution. The quotient of the slopes of the regression lines and mean of extractable Sr/Ca are also given

Soil	Extractable (Sr/Ca)($\times 10^3$)	Sr/Ca in soil solution ($\times 10^3$)	K_c	Slope of regression line [a]/ extractable (Sr/Ca)
1	12.9±0.3	13.4±0.4	0.96±0.04	0.89
1+Ca	11.5±0.7	13.4±0.2	0.85±0.05	1.20
2	5.9±0.2	7.8±0.5	0.80±0.08	2.08

[a] These slopes are those given in Table 3 for the three soils in the second harvest.

extractable Sr and Ca to the ratio of Sr and Ca in the soil solution in order to test the relevant preference of the soil for Ca or Sr. They suggested that soils having K_c values lower than 1 have a higher selectivity for Ca as compared to Sr. Selectivity coefficients for the soils used are given in Table 4 and show that the organic and the inorganic with Ca addition soil types have higher selectivities for Ca than for Sr. The preferential adsorption of Ca is highest in the organic soil. The addition of Ca in the inorganic soil increased Ca selectivity; this was probably a pH effect due to the addition of $CaCO_3$.

Differences in K_c between the soils should also be reflected in differential plant uptake. Such a differentiation is very clear if the quotients of the ratios of Sr/Ca concentrations (the slope of the regression lines shown in Table 3) in the shoots and the ratios of extractable Sr/Ca are compared with K_c. It is clear that the quotient is highest in the organic soil (lowest K_c) and lowest in the inorganic soil (highest K_c) without addition of Ca.

In Experiment 2, P addition increased the root and shoot biomass of plant species (data not shown) without affecting Ca and Sr concentrations of shoots. The interaction between P and species affected root Ca and Sr concentrations (Table 5). Concentrations of Sr and Ca were higher in shoots than in roots. Similar results for Ca were reported by Loneragan and Snowball (1969). In both plant parts and both levels of P positive linear relationship was again evident between Ca and Sr concentrations (Table 6).

The values of TF for Sr for all soil treatments and all plant species used in this study are shown in Tables 2 and 5. They were affected by species, soil type and their interaction; these values are in good agreement with those reported by Papanicolaou et al. (1991) and Peterson (1983) who used ^{85}Sr and ^{90}Sr, respectively. The quantities of the stable Sr, added in the soil in this study, were very high in comparison to quantities of radionuclides added in the soil after accidents like Chernobyl in 1986. However, we can use this index because we found a linear relationship between the Sr

Table 5. Ca and Sr concentrations in shoots, transfer factor for Sr (Sr TF) and transfer factor for Sr per Ca concentrations (Sr TF/Ca conc.) of shoots and roots for the six plant species grown in the soil 3 with and without P addition in Experiment 2

Soil treatment	Species	Shoots				Roots			
		Concentrations				Concentrations			
		Ca ($mg\ g^{-1}$)	Sr ($\mu g\ g^{-1}$)	Sr TF	Sr TF/Ca conc. ($\times 10^6$)	Ca ($mg\ g^{-1}$)	Sr ($\mu g\ g^{-1}$)	Sr TF	Sr TF/Ca conc. ($\times 10^6$)
Soil 3	*Anthoxanthum*	4.8	55	3.0	617	2.6	16	0.8	322
	Poa	5.0	83	4.5	903	2.4	21	1.1	468
	Lotus	18.1	235	12.8	705	7.2	39	2.1	295
	T.subterraneum	18.3	217	12.1	662	6.6	53	2.9	452
	T.campestre[a]	17.3	145	7.8	451	7.6	39	2.1	278
	T.tenuifolium[a]	16.6	214	11.6	699	6.7	60	2.3	336
Soil 3 + P	*Anthoxanthum*	5.7	48	2.6	458	2.3	17	0.9	411
	Poa	5.8	70	3.8	658	2.1	8	0.4	195
	Lotus	18.6	268	15.1	808	5.3	39	2.2	427
	T.subterraneum	18.3	245	13.9	761	7.5	68	3.9	526
	T.campestre[a]	16.7	167	9.0	539	7.7	40	2.2	282
	T.tenefolium[a]	16.9	207	11.0	651	6.7	60	3.3	487
	L.S.D 0.05 for								
	P				49				
	Species	0.8	20	1.2	60	0.7	7	0.4	80
	P × Species			1.7	86	1.0	10	0.6	113
	Source of variation								
	P	ns	ns	ns	*	ns	ns	ns	ns
	Species	***	***	***	***	***	***	***	**
	P × Species	ns	ns	*	***	**	**	**	***
CV, %		6.8	13.6	14.2	8.3	16.1	19.5	20.0	20.9

ns, $p > 0.05$; *, $p \leq 0.05$; **, $p \leq 0.01$; ***, $p \leq 0.001$.
[a] These two species were not included in ANOVAs, because the number of samples measured for Ca and Sr were 2 for shoots and 1 for roots.

Table 6. Linear regression equations relating Sr (in $\mu g\ g^{-1}$) and Ca (in $mg\ g^{-1}$) concentrations in shoots and roots for the six species grown with and without P addition in the Experiment 2

Soil treatment	Plant part	Equation	N	r^2
Soil 3	Shoots	Sr = 14.62 + 10.7 Ca	21	0.84***
Soil 3	Roots	Sr = 4.78 + 5.8 Ca	18	0.69***
Soil 3 + P	Shoots	Sr = -28.28 + 14.7 Ca	21	0.91***
Soil 3 + P	Roots	Sr = -8.10 + 9.3 Ca	18	0.87***

*** $p \leq 0.001$.

addition to the soil and Sr uptake by *Trifolium repens* and *Dactylis glomerata* in the range of 0 to 100 mg added Sr per pot in these soils (data not presented). Furthermore, the TF values for Sr are of the same order of magnitude using either stable Sr or other Sr isotopes (Papanicolaou et al., 1991; Peterson, 1983).

Comparisons among soils for their ability to supply Sr to plants are possible only when the same species are used. The common species used in both experiments were *Anthoxanthum* and *Lotus*. From the TF for Sr of these species (Tables 2 and 5) it is evident that the soil 3 with the lowest extractable Ca gave the highest values of TF for Sr, while the organic soil 2 having the highest extractable Ca had the lowest values of TF for Sr. For the soils used in this work, it seems that the values of TF for Sr are negatively related to extractable Ca in the soil. However, the Ca addition in the inorganic soil 1 in this study increased the Sr uptake by plants. Values of TF for Sr were also related to other soil properties like pH, C.E.C. and clay content (Papanicolaou et al., 1991). In this study the number of soils was too small to draw any solid conclusion about relations between TF for Sr and soil properties.

The high variation in the values for TF of Sr among species in each soil treatment creates difficulties in comparing soils according to their ability to supply Sr by using this index, if plant species are different in the soils used for comparisons. Since Sr concentrations in shoots and roots are positively related to respective Ca concentrations (Tables 3 and 6), TF for Sr could be improved for comparative purposes if this index is divided by the shoot (or root) Ca concentration of the respective species in a soil. The values of the new index, named "TF for Sr per Ca concentration", for all species and soil treatments used in this work are given in Tables 2 and 5. From ANOVAs it is evident that the values of this index are affected by species, soils and probably by the growth stage of plants (different harvests). However, the index TF for Sr per Ca concentration, compared to index TF for Sr, exhibited much lower variation among plant species grown in each soil treatment.

Concentrations of Sr and Ca of a particular plant part vary greatly among the various species grown in the same soil; however, these are linearly and positively related (Tables 3 and 6). For this reason the ratio of Sr and Ca concentrations among various species grown in the same soil showed much lower variation compared to those of Sr or Ca concentrations. Similar results were reviewed by Russell and Newbould (1966). Because of the close and positive relationship between Ca and Sr concentrations, we think that TF for Sr per Ca concentration could be used to compare various soils according to their ability to supply plants with Sr when different plant species are grown in these soils.

In summary it was found that, within the range of species and the small number of soils used, Sr and Ca concentrations of plant species grown in the same soil are positively related. For various soils the Sr uptake is negatively related to extractable Ca in the soil. As compared to TF for Sr, "TF for Sr per Ca concentration" exhibited much lower variation among species grown in the same soil.

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